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InGaAsN/GaAs heterostructures for long-wavelength light-emitting devices

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Abstract. We report on the growth and properties of InGaAsN/GaAs heterostructures and on their applications for lasers emitting at $\lambda \approx 1.3\,\mu$m. Structures are grown by molecular beam epitaxy using an RF plasma-source. Broad area and ridge waveguide laser structures based on such QWs exhibit performance that can compete with those of $1.3\,\mu$m InGaAsP lasers. In particular, we have achieved 300 K operation of broad area lasers at $1.3\,\mu$m with threshold current density down to 400 A/cm^2 and 650 A/cm^2 for single and triple QW structures. Similar structures with heatsinking at $10°$C yield maximum output powers of 2.4 W (cw) and 4 W (pulsed). Ridge waveguide lasers have thresholds down to 16 mA and show cw operation up to $100°$C with a T_0 of up to 110 K.

1. Introduction

InGaAsN has recently been proposed as a novel material for near-infrared lasers on GaAs and pioneering laser results were reported by Kondow *et al* [1]. When replacing the wells in InGaAs/GaAs QWs, the quaternary GaInNAs alloy allows both strain compensation and a significant decrease of the ground state transition energy. Also, an increased conduction band offset has been predicted, which should greatly improve high temperature laser performance.

Most attractively, the realisation of $1.3\,\mu$m GaInNAs vertical cavity surface emitting lasers (VCSELs) on GaAs is expected to be possible by adopting the well-established fabrication techniques for short-wavelength VCSELs based on GaAs.

In this paper we will review essential aspects of InGaAsN growth by MBE, discuss properties of InGaAsN/GaAs QWs and report state-of-the-art results on lasers which we have realised in this material system.

2. Material growth

QW test structures and laser structures were grown by solid source MBE on (001) GaAs substrates. An RF-coupled plasma source was used to generate reactive nitrogen from N$_2$. Growth proceeds much like that of InGaAs, in particular, we use As-stable conditions. It is found that at growth temperatures below $520°$C, all reactive nitrogen is completely incorporated. Thus, the N-content is only determined by the N-flux.

The experiments on growing InGaAsN heterostructures show that one of the more significant growth factors is the growth temperature [2]. The brightest and narrowest PL spectra are obtained for growth below $450°$C. As reported before [3], we find that InGaAsN heterostructures are very susceptible to post-growth heat treatment. Only by annealing at temperatures around 700 to $750°$C do we obtain a luminscence efficiency which is sufficient for high quality laser material. However, during this process, the PL peak shifts by up to

50 meV towards higher energies for strained InGaAsN QWs. Compared to this, GaAsN and InGaAsN lattice-matched to GaAs show a peak shift of less than 15 meV after the same annealing procedure. It should be noted that strained N-free InGaAs QWs do not show any significant shift in PL energy. We therefore interpret these results by a nitrogen-induced out-diffusion of In from the quantum well region.

Thermally annealed, 7 nm thick InGaAsN/GaAs QWs with In- and N-contents of about 35% and 1.7%, respectively, allow to achieve 300 K luminescence at 1.3 μm. Increasing either the N-content or the QW thickness leads to a significant reduction of luminescence intensity, such that the realisation of devices emitting at still longer wavelengths appears to be difficult.

An analysis of the PL and PLE of InGaAsN/GaAs QWs of different thicknesses in [4] has shown that
(i) the confinement energy for electrons in these structures is about 400 meV due to the fact that the conduction band discontinuity amounts to 80% the band gap difference and
(ii) that there is clear evidence for a strongly increased electron mass compared to InGaAs with the same In-content, as has been predicted in [5]. Both facts promise an excellent high temperature performance of lasers based on InGaAsN/GaAs QWs.

3.   Device application

Laser structures were grown in the optimal temperature range and annealed during the growth of the upper cladding layer. The layer sequence was chosen to be similar to those in Ref. [1]. In case of 3 QW lasers, three $In_{0.35}Ga_{0.65}As_{0.983}N_{0.017}$ QWs of 6–7 nm thickness, separated by 20 nm barrier layers, are symmetrically inserted into a 300 nm thick, undoped GaAs cavity. Best laser results were obtained by using quaternary InGaAsN barriers with the same N-content, which were lattice-matched to GaAs. The p- and n-type cladding layers consist of 1.5 μm thick $Al_{0.3}Ga_{0.7}As$, doped with Be and Si to 4×10^{17} and 5×10^{17} cm^{-3}, respectively. The 0.6 μm thick p-type GaAs contact layer is doped to $(1-5) \times 10^{19}$ cm^{-3} in the top 200 nm. Broad area lasers were fabricated by metallisation and subsequent wet-chemical etching of the p-contact layer.

3.1.   Broad area lasers

For the assessment of material quality, broad area lasers (fabricated by the shallow mesa stripe technology, width 100 μm) were characterized. The emission wavelength of all lasers referred to here is around 1.29 μm. The threshold current density of 3 QW lasers is found to decrease from 1 kA/cm^2 to less than 0.7 kA/cm^2 for cavity lengths increasing from 400 μm to 1.2 mm. The lowest threshold for $L = 800$ μm is 650 A/cm^2. Using heatsinking at 10°C, cw operation could be demonstrated for these lasers with record output powers of 2.4 W [6], which is by far the highest value ever reported so far for any wavelength in the GaInNAs material system.

Further evaluation of these lasers leads to estimated values of 81% for the internal quantum efficiency and of 10 cm^{-1} for the internal waveguide losses. By using these values and assuming in a first approximation, that the radiative and non-radiative (Auger) recombination coefficients for the GaInNAs QWs are roughly the same as for 1.3 μm InGaAsP QWs (which remains to be verified in future work) we attempted to extract the gain parameters of the GaInNAs QWs [7]. The constants g_0 and N_{tr} refer to the empirical gain-carrier-density relationship $g = g_0 \ln(N/N_{tr})$, which is used to describe the gain saturation in QWs. Values of 2800 cm^{-1} for g_0 and 2.4×10^{18} cm^{-3} for N_{tr} are obtained for our InGaAsN lasers. Both values are significantly higher than those for 1.3 μm

InGaAsP QWs where the corresponding values for g_0 and N_{tr} are found to be 1545 cm^{-1} and 1.45×10^{18} cm^{-3}, respectively. The higher values for g_0 and N_{tr} in GaInNAs are considered to be a consequence of the heavier electron mass in this material [4, 5] (m_e around $0.1m_0$, m_0 is the free electron mass).

3.2.   Ridge waveguide (RWG) lasers

Narrow-stripe RWG lasers were processed by using Ar ion dry etching technique for the ridge formation. Stripe widths of 3.5 μm were realised, passivated with RF-sputtered SiN$_x$. After conventional p- and n-contact formation chips were mounted epi-side up on copper heatsinks for detailed characterization.

The pulsed light-current characteristics of 350 μm long as-cleaved RWG laserdiodes at room temperature show threshold currents as low as 21 mA as well as efficiencies of 0.25 W/A per facet. To the authors' knowledge both values represent improvement factors of $>$ 2 and 1.5, respectively, as compared to previously published results [8]. At 90°C the threshold current increases above 50 mA but even at 100°C lasing operation could be maintained. As above, the emission wavelength is around 1290 nm at room temperature.
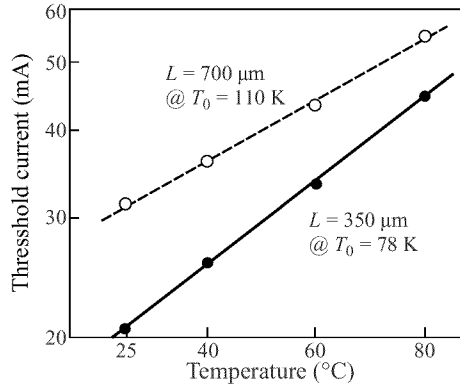
Fig. 1. Temperature dependence of the threshold currents of as-cleaved ridge-waveguide lasers of two different lenghths.

The temperature dependence of the threshold current is shown in Fig. 1 for 350 μm and 700 μm long as-cleaved devices. The corresponding values for T_0 are 80–90 K and around 110 K, respectively. These values compare favorably to those of 1.3 μm InGaAsP RWG lasers, where values around 70 K are typical.

The performance of 2 QW devices with a one-side highly reflection (HR)-coating (reflectivity $\sim$75%) was also investigated [9]. Threshold currents of only 16 mA and differential quantum efficiencies of 0.35 W/A were measured at 25°C, while at 80°C the corresponding values are 33 mA and 0.25 W/A, respectively.

First measurements of differential gain of InGaAsN QW lasers were performed and yield values similar to InGaAsP lasers ($dg/dN = (5 \pm 1) \times 10^{-16}$ cm^2). This comparison indicates that also InGaAsN-based 1.3 μm LDs will be suitable for use as transmitters in high speed transmission systems.

Also, first lifetime tests at accelerated aging conditions (operation at 80°C with a current of 100 mA cw, corresponding to a current density of 6 kA cm^{-2}) show no noticable degradation of the threshold current after more than 700 h.

4. Conclusion

In summary, we have demonstrated low threshold current density CW operation of MBE-grown InGaAsN lasers at wavelengths of about 1.3 μm. Their performance is comparable to InGaAsP lasers emitting at the same wavelength, but they have the advantage of a significantly enhanced T_0. The combination of the active region used in present work with GaAs/AlAs DBR-mirrors is expected to lead to novel vertical cavity lasers for optical fiber communication systems.

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